Efficient Bell State Measurement with Time-Bin Qubits

UNIVERSITY OF CALGARY

Institute for QUANTUM SCIENCE AND TECHNOLOGY at the University of Calgary

NIST

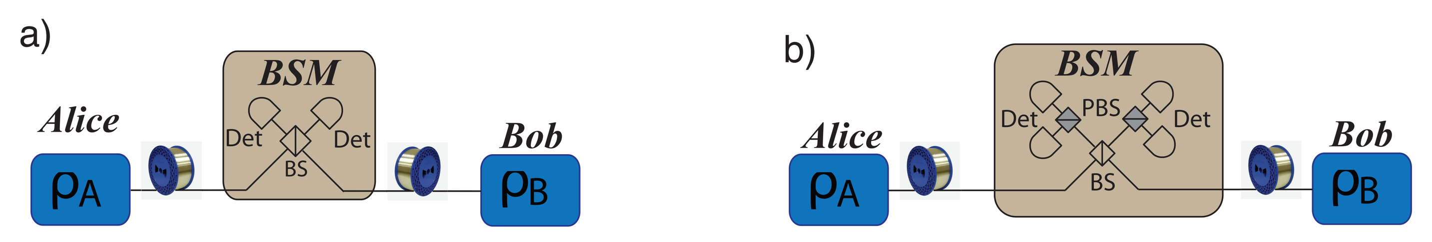
JPL Jet Propulsion Laboratory California Institute of Technology

I. Lucio-Martinez[1,2], P. Chan[1,3], R. Valivarthi[1,2], J. A. Slater[1,2], F. Marsili[5], V. B. Verma[4], J. A. Stern[5], M. D. Shaw[5], D. Oblak[1,2], S. W. Nam[4] and W. Tittel[1,2]

1 Institute for Quantum Science and Technology, University of Calgary, 2 Department of Physics and Astronomy, University of Calgary
3 Department of Electrical and Computing Engineering, University of Calgary, 4 National Institute of Standards and Technology, 5 Jet Propulsion Laboratory, California Institute of Technology

1. Introduction

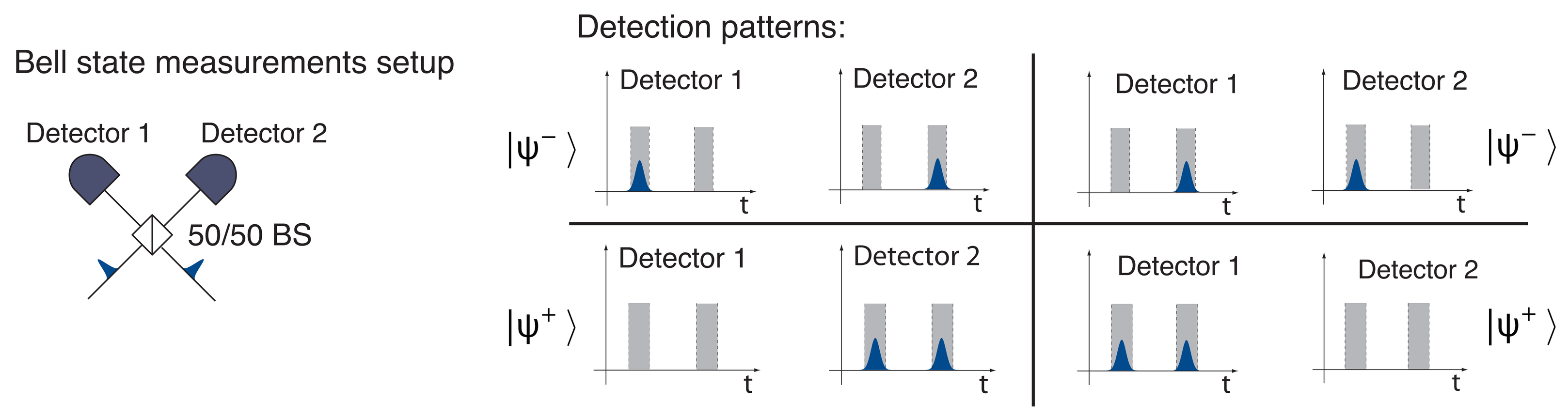
Bell state measurements (BSMs) play a key role in linear optics quantum computation and many quantum communication protocols, e.g. quantum repeaters [1] and quantum teleportation [2].
A complete BSM allows projecting any two-photon state onto the set of four maximally entangled Bell states, i.e. $|\psi^{\pm}\rangle$, $|\varphi^{\pm}\rangle$. Using linear optics and no auxiliary photons, this measurement can, in principle, only succeed with 50% probability [3]. The standard approach uses a 50/50 beam splitter (BS) followed by two detectors that allow discriminating between orthogonal polarization or temporal modes, as required for BSMs with polarization or time-bin qubits, respectively. (This discrimination can be accomplished by adding polarization beam splitters in front of each detector, or by using detectors with sufficient temporal resolution.) The standard BSM allows unambiguous identification of projections onto $|\psi^-\rangle$, in which case the two photons exit the BS through two different outputs and in orthogonal polarization or temporal modes, and projections onto $|\psi^+\rangle$, in which case the two photons exit the BS through the same output and in orthogonal polarization or temporal modes. All other coincidence detections (i.e. both photons exiting in the same polarization or temporal mode) project onto product states.



Bell-state measurement setup for time-bin qubits (a) and polarization qubits (b).

2. The problem

- Time-bin qubits are often used in QKD systems as they are easy to implement.
- There are technological challenges when performing BSMs with time-bin qubits as a projection onto $|\psi^+\rangle$ happens when one of the detectors registers an event in both the early and late time-bins, see figure below.
- Due to long recovery times of most single photon detectors (on the order of a few µs), typical implementations only measure projections onto the $|\psi^-\rangle$ state.
- This technological obstacle translates into a success probability of the BSM of maximally 25%,

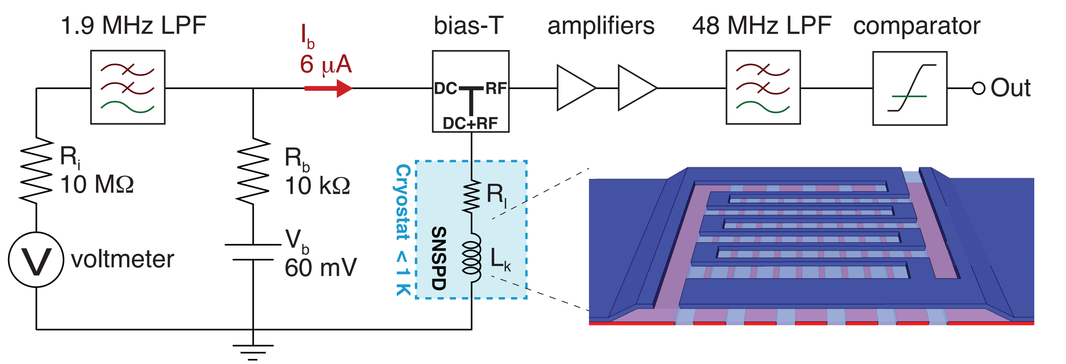


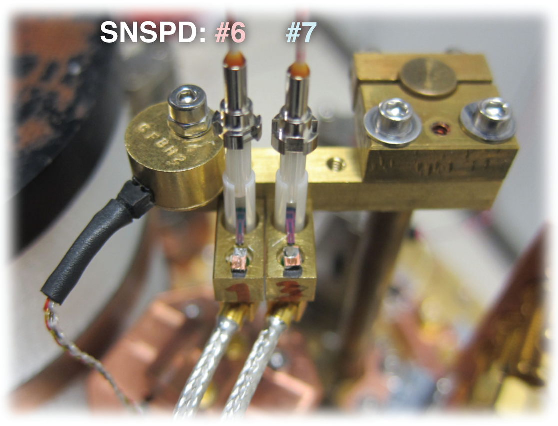
3. The solution

Superconducting Nanowire Single-Photon Detectors (SNSPD) based on tungsten silicide (WSI) developped and fabricated at the National Institute for Standards and Technology (NIST).

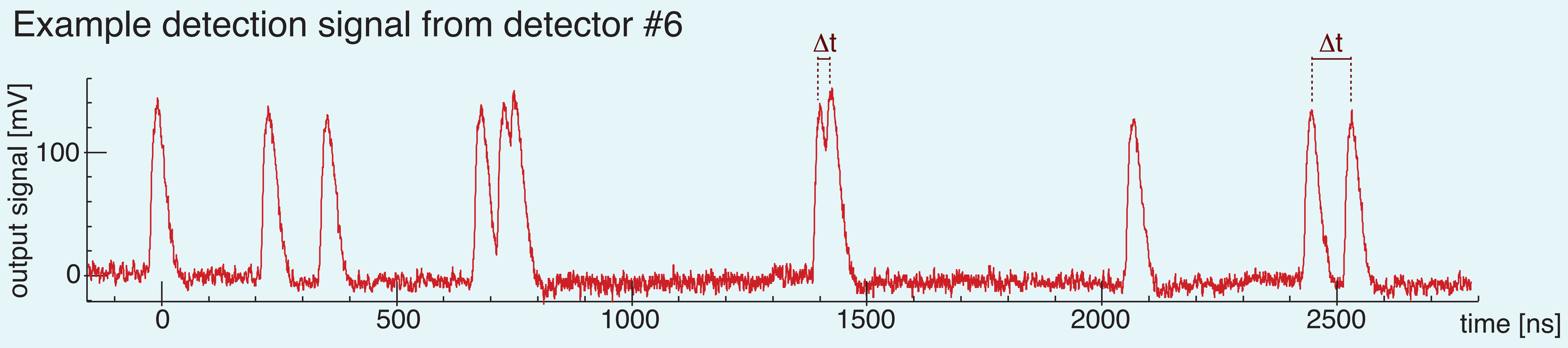
- \+ High efficiency (up to 93%) at 1550 nm wavelength [6] with low polarization sensitivity [7]
- \+ Free running
- \+ No afterpulsing and low dark count level ≈ 1 Hz
- \+ Short recovery time $\tau < 100$ ns

Electrical diagram:



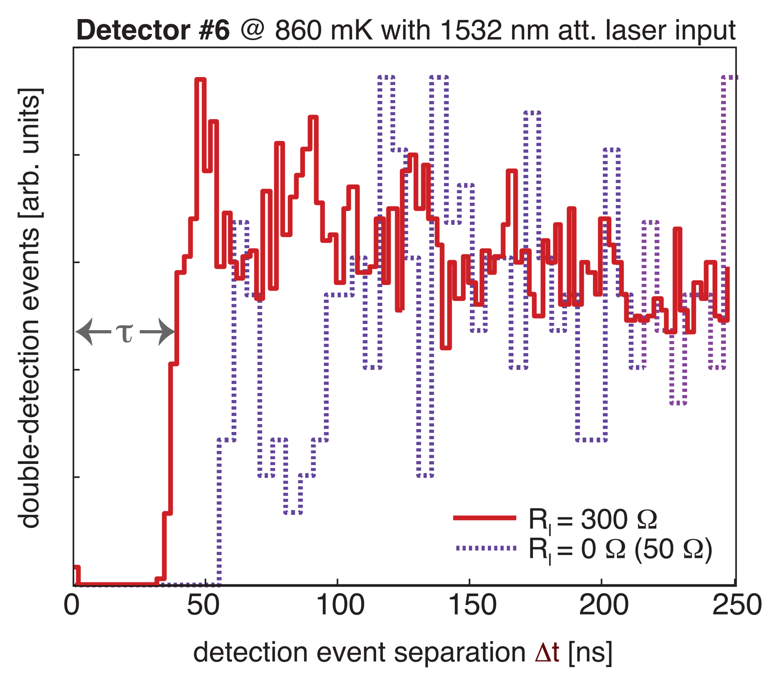


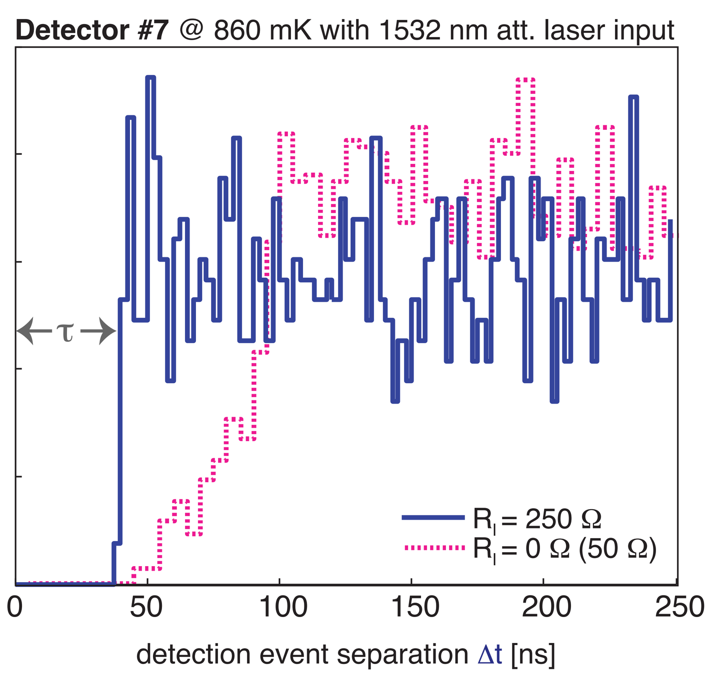
Example detection signal from detector #6



Reducing deadtime τ from ≈100 ns to ≈40 ns

$\tau \sim L_k/R_l$: Kinetic inductance L_k fixed => add additional load resistor R_l [8]

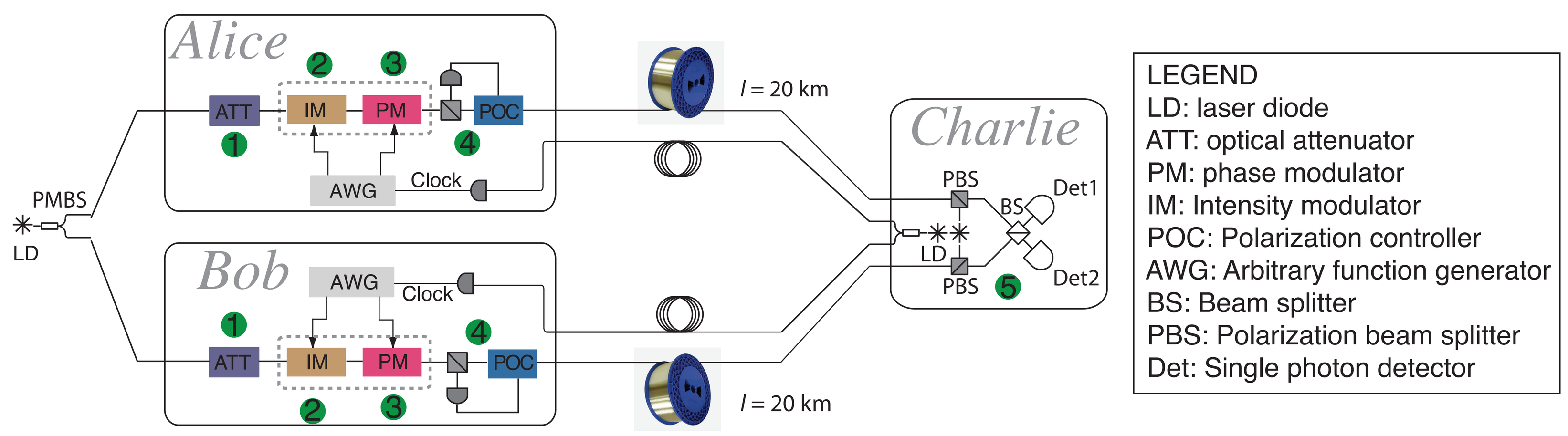




4. Setup

The setup is similar to that for measurement-device-independent quantum key distribution (MDI-QKD) [4,5]. Information about the quality of the BSM can be derived despite the use of attenuateed laser pulses.

- All-fiber-based implementation
- Source light at 1550 nm
- Attenuated laser pulses
- Test implemented using time-bin qubits
- Optical pulse width: 1 ns FWHM
- Time-bin separation: 75 ns
- Repetition rate of 5 MHz



1. Light is attenuated to the single photon level
2. Optical pulses are carved/basis selection
3. Quantum state preparation
4. Polarization stabilization system
5. Bell state measurement

5. Results

We have measured the quantum bit error rate (QBER) for Alice and Bob sending states prepared either in the the z-basis (spanned by the states $\{|0\rangle,|1\rangle\}$), or the x-basis (spanned by the states $\{|+\rangle,|-\rangle\}$). The experimentally obtained error rates follow the theoretical predictions (see table below). Note that the QBER in the x-basis has a lower bound of 25%. This is due to the possibility that one source emits two photons and the other source emits no photon, which can result in the detection pattern associated with projections onto $|\psi^-\rangle$ and $|\psi^+\rangle$. However, the existence of multi-photon pulses does not lead to errors when sending equal states prepared in the z-basis, as projections onto orthogonal polarization states or different temporal modes do not happen.

Average mean photon number: μ≈0.2		$|\psi^-\rangle$ projections		$|\psi^+\rangle$ projections	
		z-basis	x-basis	z-basis	x-basis
QBER (%)	Theory	0	25	0	25
	Experiment	0.32± 0.02	26.64 ±0.11	0.33 ±0.02	26.92 ±0.10

6. Conclusions and Outlook

- The fast recovery time of SNSPDs allows increasing the success probability for BSMs with time-bin qubits by a factor of two.
- Together with the high quantum efficiency of the SNSPDs, this improves the success probability by a factor of 60 as compared to a BSM with InGaAs avalanche photodiodes.
- The low noise of the detectors allows for a low QBER.
- SNSPDs benefit MDI-QKD, quantum repeaters and linear optics quantum computation.
- Further detector improvements include decreasing the recovery time.

References

[1] N. Sangouard et al, Rev. Mod. Phys, **83**, 33 (2011).
[2] C.H. Bennett et al, Phys. Rev. Lett., **70**, 1895 (1993).
[3] N. Lütkenhaus et al, Phys. Rev. A, **59**, 3295 (1999).
[4] H.-K. Lo et al, Phys. Rev. Lett., **108**, 130503 (2012).
[5] A. Rubenok et al, arXiv:1304.2463.
[6] F Marsili et al, Nature Photonics, **7**, 210 (2013).
[7] V Verma et al, Appl. Phys. Lett., **101**, 251114 (2012).
[8] JKW Yang et al, IEEE Trans. on Appl. Supercond., 17:2 (2007).

NSERC CRSNG
Alberta Innovates Technology Futures
DARPA DSO DEFENSE SCIENCES OFFICE
Quiness Program
Grant No.
W31P4Q-13-1-0004.
Les Fiducies Killam Trusts
Carlsberg CARLSBERGFONDET
DARPA INPHO PROGRAM